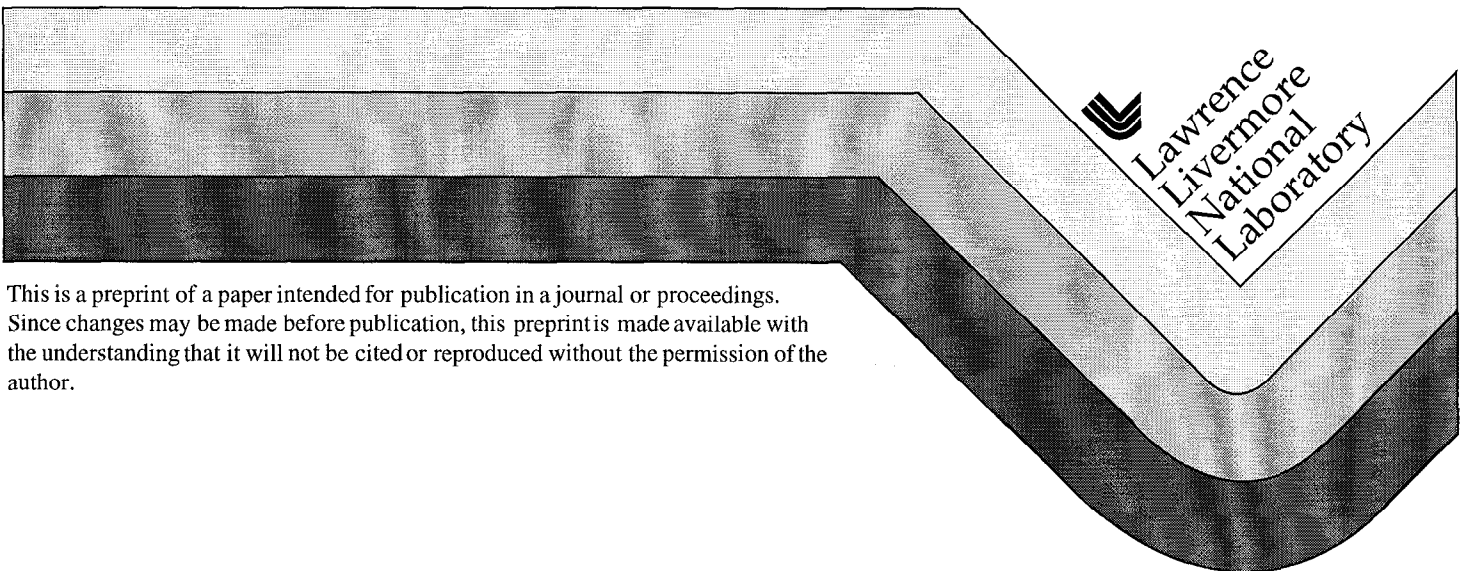


# **WET MARS: Plentiful, Readily-Available Martian Water and Its Implications**

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# WET MARS:

## Plentiful, Readily-Available Martian Water and Its Implications\*

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### ABSTRACT

*Water and its major constituent, oxygen, in large specific quantities are essential for maintenance of human life. Providing them in adequate quantities is widely believed to be a major challenge for human Mars exploration and settlement. The Martian regolith isn't known to bear either water or hydrogen, the ice-rich Martian polar regions are thermally inhospitable, and the measured water content of Mars' thin atmosphere represents a layer of liquid water of average thickness only about 1% that of the Moon: ~0.001 cm. Crucially, however, the atmospheric Martian water inventory is advected to everywhere on Mars by meteorological phenomena, so that the few cubic kilometers of liquid water-equivalent in the atmosphere are available most anywhere when, merely for the effort of condensing it.*

*Well-engineered apparatus deployed essentially anywhere on Mars can condense water from the atmosphere in daily quantities not much smaller than its own mass, rejecting into space from radiators deployed over the local terrain the water's heat-of-condensation and the heat from non-ideality of the equipment's operation. Thus, an optimized, photovoltaically-powered 0.3 ton water-condensing system could strip 40 tons of water each year from ~10<sup>4</sup> times this mass of thin, dry Martian air.*

*Given a 480 sec I<sub>sp</sub> of H<sub>2</sub>-O<sub>2</sub> propulsion systems exhausting into the 6 millibar Mars-surface atmosphere and the 5.0 km/s Martian gravity well, ≤40 tons of water two-thirds converted into 5:1 O<sub>2</sub>/H<sub>2</sub> cryogenic fuel could support exploration and loft a crew-of-four and their 8-ton ascent vehicle into Earth-return trajectory. The remaining water and excess oxygen would suffice for half-open-cycle life support for a year's stay on Mars.*

*A Mars Expedition thus needs to land only explorers, dehydrated food, habitation gear and unfueled exploration/Earth-return equipment – and a water/oxygen/fuel plant with embedded power supply which operates on Martian atmospheric water. All of the oxygen, water and propellants necessary for life-support, extensive exploration and Earth-return can be provided quite readily by the host planet.*

*The most challenging technical problem with respect to human expeditions to Mars is that of escaping from Earth's deep, 11.2 km/s gravity well. Living on Mars, exploring it extensively and returning to Earth each are technically much less difficult, thanks in no small part to the effective 'wetness' of Mars.*

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**Introduction And Summary.** Water is the sine qua non of human life. Not only is it essential *per se* for use in preventing eventually-fatal dehydration of our tissues, but its major constituent, oxygen, is essential in molecular form as the ultimate electron-sink in the chemical reactions which power all human metabolic processes. We die without oxygen gas for respiration in a matter of minutes, without liquid water for rehydration in a handful of days. To stay alive, then, we must immerse ourselves in environments which aren't completely water-poor, just as our distant ancestors required enormously water-rich ones.

Off-Earth human exploration and settlement appears especially challenging, then, for liquid water is known to be present in very few locations of near-term interest for exploration of the inner Solar system – actually, precisely none. The general mind-set has been that Mars is exemplary of such water-starved, innately inhospitable locales, for the very modest quantities of water which exist on its surface – by terrestrial standards, at least – seem to be tightly locked-up in polar caps of forbiddingly low temperature. Even the vacuum-enshrouded Moon, from our current, relatively poorly-informed perspective, might seem more attractive to water-addicted species such as our own, for its generally fine-powdery surface is known to have several ppm of solar wind hydrogen implanted in it, which can be released by moderate roasting of this 'soil.' The corresponding amount of water-equivalent hydrogen in the top dozen meters of continually meteorically-churned lunar regolith is a liquid sheet of about 0.1 cm thickness, or 1000 metric tons of water per square kilometer of *mare* surface – everywhere! The dusty, wind-swept Martian surface seems desert-like in comparison.

The purpose of this paper is to invite general attention to the facts ***that Mars is actually reasonably water-rich, that the entire surface of Mars is truly covered with a very low-density albeit deep ocean of water – and that human exploration and settlement of Mars are thereby much less demanding than has been generally believed.***

In particular, as specialists have long understood, the Martian atmosphere has the same specific water content as is found in the Earth's air over Antarctica – about 1 milliTorr vapor pressure – and the transport properties of the Martian atmosphere are particularly conducive to condensation of this atmospheric moisture with modest specific quantities of equipment. Deployment and operation of quite small amounts of optimized equipment may readily extract enough liquid water to not only provide the feedstreams of oxygen and water to life-support systems for human explorers or settlers, but can also provide the several-fold greater quantities of liquid hydrogen and liquid oxygen needed to support vigorous rocket- and ground-vehicle-supported exploration of Mars, as well as rocket-powered return-to-Earth from the Martian surface. (Indeed, extracting water from the Martian atmosphere *per se* is far from conceptually novel.)

***Martian explorers and settlers thus need bring to Mars little more than themselves, life-support and habitation equipments, dehydrated food sufficient until greenhouse operation provides adequate foodstuffs, and exploration and Earth-return vehicles.*** Water extracted from the Martian atmosphere will fill in the remainder of the traditional expedition's mass-budget – and this mass budget-

fraction typically is the dominant one. ***Exploration and settlement of Mars thereby may be several-fold easier, in terms of required mass leaving the Earth in trans-Mars trajectory, than has been estimated hitherto – and thus may be made to commence significantly sooner.***

In the following sections, we first review salient properties of the Martian atmosphere, including its meteorological repertoire, then consider the form-and-function of equipment mass-optimized to extract water from it, note the quantities of water of interest to support the full spectrum of activities of early exploration teams, and conclude with suggestions for the steps to be taken toward the reasonably near-term implementation and demonstration of these prospects.

**Pertinent Properties Of The Martian Atmosphere.** Our present knowledge of the pertinent features of the Martian atmosphere is derived from the Viking Lander 1 and 2 data-sets, supplemented by the Pathfinder results of 1997. The Viking data is of primary interest, as it represents essentially all that we know of a quantitative nature about Martian atmospheric seasonality – and because it sampled atmospheric properties at two quite different locations on Mars; at that, it's quite imperfect, as surface-level water vapor concentrations were measured only indirectly and only two sites on Mars, a planet whose meteorology apparently is not much less rich than that of the Earth, were studied for only over a single full year's variations, i.e., 650 sols.

The primary data of present interest is summarized in Figure 1, which, at the bottom line", indicates that the global annual average of water content of the Martian atmosphere is  $2 \times 10^{-6}$  kg/m<sup>3</sup>, corresponding to a bit more than 1 milliTorr vapor pressure. The right vertical axis of this Figure indicates the saturation temperature for different water vapor pressures. As may be readily appreciated, the saturation temperature for the global annual-averaged water vapor pressure is about -74° C, or 199 K, while an order-of-magnitude lower vapor pressure is seen at -88° C, or 185 K, and another order-of-magnitude reduction is seen at -100° C, or 173 K.

Stripping water out of the "average" Martian atmosphere thus consists of cooling it to a temperature of no more than about 185 K, providing a convenient surface onto which this now-supersaturated Martian 'air' can deposit and/or grow ice crystals, and maintaining this condition sufficiently long for essentially all water molecules in the parcel of chilled air to "see" the ice-covered surface via diffusive-and-convective transport. This whole process really isn't very complicated – splotchy hoar frosts on the nearby Martian surface were imaged regularly during local wintertime shortly after dawn at the Viking Lander sites.

**Mass-Optimized Water Extraction From The Martian Atmosphere.** *The issue of present interest is the design of equipment of minimum mass with which a unit quantity of water can be extracted from the Martian atmosphere per unit of time.*

As we will also mention quantitatively below – but which is intuitively obvious to those who have considered these matters in any detail – the present and near-term

specific cost of soft-landing equipment on the Martian surface is so great that it exceeds the specific cost on the Earth's surface of virtually every type of human artifact. Simply stated, the per-pound transportation cost from Earth-surface to Mars-surface is so huge that it exceeds the purchase-cost here on Earth of essentially everything. It is therefore "good engineering practice" in the design process to drive the mass of *any* equipment that needs to go to Mars to as low a value as ever possible; no matter how expensive it may then be to fabricate, the total cost to create and then haul to Mars will thereby be minimized. This is the approach which we take the optimized design of equipment for extracting water from the Martian atmosphere.

Our basic approach is to use counter-current air-flow through the water-condenser, and cool-as-required the coldest spot ( $T \leq 180$  K) in the system radiatively; as noted above, water starts condensing from the most moist Martian air at  $\sim 200$  K, and 95+% (global- and time-averaged) is stripped out at 180 K. The condenser's incoming and exhaust air-flows are cross-coupled thermally with heat-pipes terminating on each side on super-high surface-to-volume metal-to-gas finned/spiked surfaces. Photovoltaically-energized electric motor-driven fans make up condenser-internal aero-drag losses (with  $H_2/O_2$  fuel cell-derived power being employed during nighttimes and dust storms).

The core technical issue in overall system design is trading off condenser drag-loss vs. condenser mass vs. condenser air-blower electrical power (i.e., PVA, power-conditioning and fuel-cell masses) vs. condenser irreversible  $\Delta T$  (the temperature differential between the exhausted air relative to the incoming air arising from finite air flow-speeds and imperfect heat-exchange), in order to minimize total system mass (including that of the system's radiator, which sizes and masses nearly linearly in proportion to  $\Delta T$  – exactly linearly, after the 'base'  $2.5 \times 10^8$  J/day –  $\sim 2.5$  kW – of heat-of-condensation of 100 kg of water/day is subtracted off the bottom of the system's thermal radiation budget). The only major constraint on the radiator is that its working-surface be shaded, *if* it's going to be operated in daytime, as well as nighttime; it *may* thus be split into AM and PM sections (*if* it's deployed in east-west symmetry; splitting is less necessary if deployed in north-south symmetry). A minor radiator constraint is that it's operating in 6 mbar 'air', so that it needs some 'standard' thermal decoupling, with associated mass-expenditure.

Our scoping estimate is that the  $\sim 10^9$  gm/day of Mars-air – processed through the  $\sim 10^2$  m<sup>2</sup> condenser system inlet at 10 m/sec mean speed – will require of the order of  $10^9$  J (or  $\sim 10$  kW, CW) of heat stripped from it, net; this corresponds to a flow-stream irreversible  $\Delta T$  of 1 J/gm-equivalent, or 44 J/mole (of  $CO_2$ ), or  $\sim 10$  cal/mole, or  $\sim 1.5$  K  $\Delta T$ , split into two roughly-equal portions, in the metal-to-air interfaces on each side of the counter-current flow (with the interposed heat-piping being taken to be a thermal superconductor, which is a quite good approximation). This is  $\sim 5\%$  of the total temperature change which the processed air typically (i.e., in the diurnal-average) will be cycled through, so that the mean-reversibility of the condenser system is taken to be 95%. (We expect that this flow-speed will suffice for centrifugal separation of all but the smallest dust particles from the inlet air-stream, given the low density of the flow; electrostatic precipitation will then serve

to "polish" the flow with respect to very small dust particles, so that minimal processing of the extracted water will be required prior to storage or electrolysis.)

If the Martian air-mass exits the 100 m<sup>2</sup>-aperture condenser with the reference entry-speed of 10 m/sec, this represents only 850 W of kinetic energy, likely a modest fraction of the total power budget of the system, so that use of pressure-recovery means probably isn't indicated. A simple electrically-powered blower-system provides the necessary ventilation of the condenser. An electrical-watt-to-flow-watt efficiency of ~0.71 is realistic for the high Reynolds number conditions characteristic of the Martian surface atmosphere, assuming use of a 95% efficient fan-motor.

The radiator, working at 175 K at an emissivity of 0.85, sheds (into 2 $\pi$  steradians) about 50 W/m<sup>2</sup>, so that 200 m<sup>2</sup> is required to shed 10 kW; the radiator's area thus is comparable to the sum of the entry and exhaust port-areas of the condenser. (The Martian atmosphere is radiatively *reasonably* thin in the thermal IR – the current Martian 'atmospheric greenhouse'  $\Delta T$  is only ~7 K, compared to ~35 K for Terra – so the radiator performs *almost* like it's radiating directly into space, except that only one side of it is available to shed heat, and the ambient air-&-soil must be kept out of effective thermal contact with the radiator's cold surface). The radiator's surface will be shaded from direct or indirect illumination by either the Sun or the Martian surface, e.g., will be north-facing in northerly latitudes, with suitably thermally-decoupled baffles-&-shades positioned to keep it 'looking' only into non-Sun-bearing space; the Martian equatorial inclination to its orbital plane is 24°.

If it's deemed too tedious to shield the radiator from the Sun-&-surface, the condenser may be operated only when the Sun is below the local horizon, and employ a simple radiator lying on the local surface, looking into the entire 2 $\pi$  of the dark sky. In this case, the entire [condenser+radiator+fuel cell] subsystem must be oversized by two-fold, relative to the operating-all-the-time baseline system, and the photovoltaic array (PVA) simply 'pumps up' the store of cryogenic H<sub>2</sub> and O<sub>2</sub> during daytime, for nocturnal fuel-cell use. This variant is considered likely to be off the mass-optimum, however; it's of interest only if total system simplicity – and (perceived) technical risk – is at a premium.

Periodically – e.g., diurnally – the system will (hermetically) close its entry-and-exit hatches and electrically heat its "cold-spot" to ~275 K, so as to liquefy the condensed H<sub>2</sub>O and gravity-drain it into a sump for pump-transport to electrolysis-&-cryogen storage, to water storage, etc. (The molten-water vapor pressure at 2-3° C will add only ~6 mbar to the condenser-internal pressure, so that a high-strength shell around the condenser and its hatches is quite unnecessary to contain the internal gases during the system's 'defrost cycle'.) The system then radiatively re-cools to working temperatures (in order to scavenge internal liquid water and water-vapor), its hatches re-open and atmospheric water-condensing resumes.

The condenser system likely will be implemented with many identical modules working in parallel, for reasons of economy in Earth-side prototyping and testing, of simplicity of packaging-for-transit, of ease-of-erection and of system-level reliability-in-operation. Thus, the condenser *per se*, the radiator and the PVA functions probably will be fully-integrated in each module, so that there will be

precisely no common-mode failure-points in the total system – and so that the system's capacity could be readily "cut-to-length" to meet varying mission requirements.

Insolation at Mars diurnally-averages about  $150 \text{ W/m}^2$ , or about  $15 \text{ W/m}^2$  electrical converted with a-Si, or  $30 \text{ W/m}^2$  converted with high-efficiency, thinned Si. Electrolyzing the (time-averaged) 1 gm/sec of water condensed will require ~15 kW electrical power, or the output of 500-1000  $\text{m}^2$  of PVA. The best-current a-Si offers about 1 W/gm at 1 AU AM0, and the comparable value for high-efficiency 4-mil Si is ~0.5 W/gm, so that a 15 kW power requirement requires ~35 kg of a-Si PVA, or ~70 kg of PVA when using thin-crystalline Si, at Mars AM1; a-Si usage is therefore somewhat preferred. An option which we consider interesting but haven't examined in detail features double-use of one-and-the-same large-area deployed surface: as a PVA during daytime and as a radiator-surface at night. If this is done, 400  $\text{m}^2$  of effective surface area is required if we condense-and-radiate only at night, which is roughly equivalent to the 500-1000  $\text{m}^2$  of PVA needed during daytime. If we employed a 1000  $\text{m}^2$  area, the 2.5X larger radiator surface area would permit us to operate with a irreversible  $\Delta T$  which is 2.5X greater, i.e., ~4 K, realizing a corresponding savings in condenser system mass. However, such double-use doesn't come free; we would likely have to provide some degree of thermal insulation of the underside of the entire area, in addition to atmospherically-decoupling both its top and bottom surfaces, in order to thermally decouple the underside from the soil usefully soon after sunset. Thus, unless suitable {atmosphere+soil} insulation of quite modest areal density –  $<0.05 \text{ gm/cm}^2$  – is available, we might be better off with employing a crystalline-Si PVA and working with the smaller 1.5 K  $\Delta T$  in the condenser's air-flow.

These, then are the essential considerations upon which our baseline-design system mass-estimate of 300 kg (0.3 tonne) is based. We allocate 70 kg to the PVA, 120 kg additional to the condenser, 15 kg to fans and pumps, 5 kg each to power conditioning, fuel-cell, electrolytic cell, cryogen liquefaction, and control system, 20 kg to polyaramid-implemented, bladder-type water storage and 50 kg to similar-type cryogen storage (all bladders being double-walled with intra-positioned lofted-fiber insulation). Clearly, we contemplate the pervasive use of high strength-to-weight structural materials and highly mass-economized (e.g., thin-walled) fins, heat-pipes, etc. – and we exploit the fact that Martian winds, though occasionally of very high speed (~200 km/hour), have only the peak momentum flux density of a brisk Terran breeze. At that, our baseline design requires the use of nothing which isn't commercially sourced at the present time.

In concluding this section, we feel obliged to note briefly a lower-likelihood but high-payoff alternative to the approach which we've just outlined. It proposes to exploit the meteorological prospect of reliably-appearing nocturnal fogs, which naturally raises the corresponding technical prospect of erecting large-area, Cottrell-type electrostatic precipitators through which the ambient 2-4 m/sec Martian nocturnal breeze would blow the ice/water-droplet-laden Martian atmosphere. The fog would be condensed on the precipitator plates, and the whole precipitator assembly would button itself up in a gas-tight manner shortly after local dawn; later in the day, it would electrically heat the precipitator plates to melt the deposited ice-film and



such a system, with an aperture of  $\sim 1000 \text{ m}^2$  – 10 X our baseline case of  $100 \text{ m}^2$ , one factor-of-3 due to the average wind speed being lower than our forced-convection speed and the other due to only 33% duty-cycle, i.e., during the coldest third of the local diurnal cycle – might be quite mass-competitive overall with the system just outlined.

If such a system were implemented in a very highly mass-economized, Venetian-blind-like format, it might be feasible to deploy it by simply unrolling its base across the local landscape, and then erect it from this base, all perpendicular to the prevailing diurnal wind direction. Although the electrical power required to operate such a system would be far smaller than that for the baseline system, a fair-sized PVA would still be required in order to convert the large majority of the electrostatically-stripped Martian atmospheric water to cryo-propellants and to  $\text{O}_2$  for the life-support system. Thus, if nocturnal fogs appear reliably at the expedition's landing-site, then God graciously condenses the water from Martian atmospheric water vapor most every night, and harvesting it from the air by the figurative waving of electrostatic wands is all that Man need do for his mundane purposes.

**Early Expedition Water Budgets And Sizing Of Water-Supply Equipment.** We use results from our previous work on the Space Exploration Initiative – i.e., the *Great Exploration Program* proposal – for reference mass-budget numbers for a first manned expedition to Mars. See Figure 2.

These indicate a requirement for of the order of 0.1 tonne – 100 kg – of water per day, or 1 gm/second, in the time-average, over the duration of the 400-day stay of the expedition crew on the Martian surface, or 40 tonnes of water total. This rate of water-production will suffice for all life-support system needs, all energy requirements for vigorous, long-distance surface rover- and rocket- performed exploration of the Martian surface and all fueling requirements for the ascent stage of the crew's return-to-Earth vehicle. See Figure 3. It represents over 80% of the total mass which is landed in a conventional Mars exploration mission which brings life-support water and oxygen and Earth-return propellants down the Martian surface from the Earth.

The first-level breakdown of this mass-budget is as follows: each of the crew-of-four needs about 3 kg/day of ( $\sim 1 \text{ kg}$  respiration consumption +  $\sim 2 \text{ kg}$  leakage make-up) oxygen for 700 days after Mars-touchdown (400 days on Mars and 300 days of Mars-to-Earth return journey) and 0.5 kg day of water (for leakage make-up, assuming full water-recycling). This aggregates to 8.4 tonnes of  $\text{O}_2$  and 1.4 tonnes of water.

The ascent-stage propulsion-plant is taken to be RL-10-based, and will exhaust a 5:1  $\text{O}_2/\text{H}_2$  propellant-mix; it'll require about 15 tonnes of this propellant mix to inject an 8-tonne return-to-Earth module into a trans-Earth trajectory from the Martian surface. Martian surface exploration is assumed to require another 9 tonnes of this propellant-mix to fuel the Hop-About for about a dozen ballistic-flight forays to sites roughly equally spaced all over the Martian surface. These requirements aggregate to a total demand of 28.4 tonnes of  $\text{O}_2$ , 4 tonnes of  $\text{H}_2$  and 1.4 tonnes of  $\text{H}_2\text{O}$  *per se*; this is equivalent to about 37.4 tonnes of water, with 3.6 tonnes of  $\text{O}_2$  to spare. It's therefore appropriate to scale the water-plant to produce 40 tonnes of water

during the 400 day stay-duration, i.e., to average a daily production of 100 kg, or 1 gm/second – all as foreseen above.

**Moving Out From Here.** The present work represents another step down the path first charted by Robert Zubrin – with his proposal for a landed [methane-generating plant+hydrogen feedstock] – of innovatively exploiting indigenous Martian resources to drive down the mass cost – and thus the dollar cost – of mounting even the first human expeditions to Mars. Ours is a "philosopher's stone" gambit, which aims at generating essentially all the consumables ever needed thereafter by the as-landed expedition from readily available local feedstreams – Martian air and ambient sunlight – with a single system consisting of a handful of readily-available or -fabricated components: *water-condenser, radiator, water-electrolytic cell,  $H_2/O_2$  liquefaction unit, cryogen and water storage-bottles and a photovoltaic array.*

*The beauty of the present gambit is that it substitutes equipment having about 1% of the mass of the materials generated for the far greater mass of the materials themselves.* Indeed, it's readily feasible to send a full-scale system of this type to the Martian surface on a *single Atlas-Centaur-class launch* inserting an aerobraked descent package into trans-Mars orbit, to deploy it and put it into operation robotically once it's landed, and then to operate it until its water and cryogen tanks all are full. A manned expedition, perhaps carrying a back-up water-plant, could then leave for Mars in a several-fold smaller – and corresponding less expensive – total package than is currently contemplated.

It might be reasonable to first design, then to prototype in sub-scale, and then to build in full-scale such a water-plant for Earth-side evaluation. Such evaluation presumably would culminate in an environmental chamber which duplicates the key features of the Martian surface, atmosphere and sky – and likely would involve a water-plant implemented in something like 1% of full scale. Once the basic design had thereby been qualified and a full-scale one had been deployed satisfactorily in Earth-surface simulation from an as-landed package, it would be appropriate to send the full-scale system to Mars for the real field trials. Even the first such trial could lay the foundation for a follow-on manned expedition very soon thereafter, if it were fully successful.

A program of this type might even fit aptly within a NASA *Discovery* programmatic time-and-dollar envelope – if it were planned and executed in a thoroughly competent and reasonably innovative manner. As such, it would constitute a remarkably low-cost, short-time enabler of remarkably large proportions for the first crewed expedition to Mars.

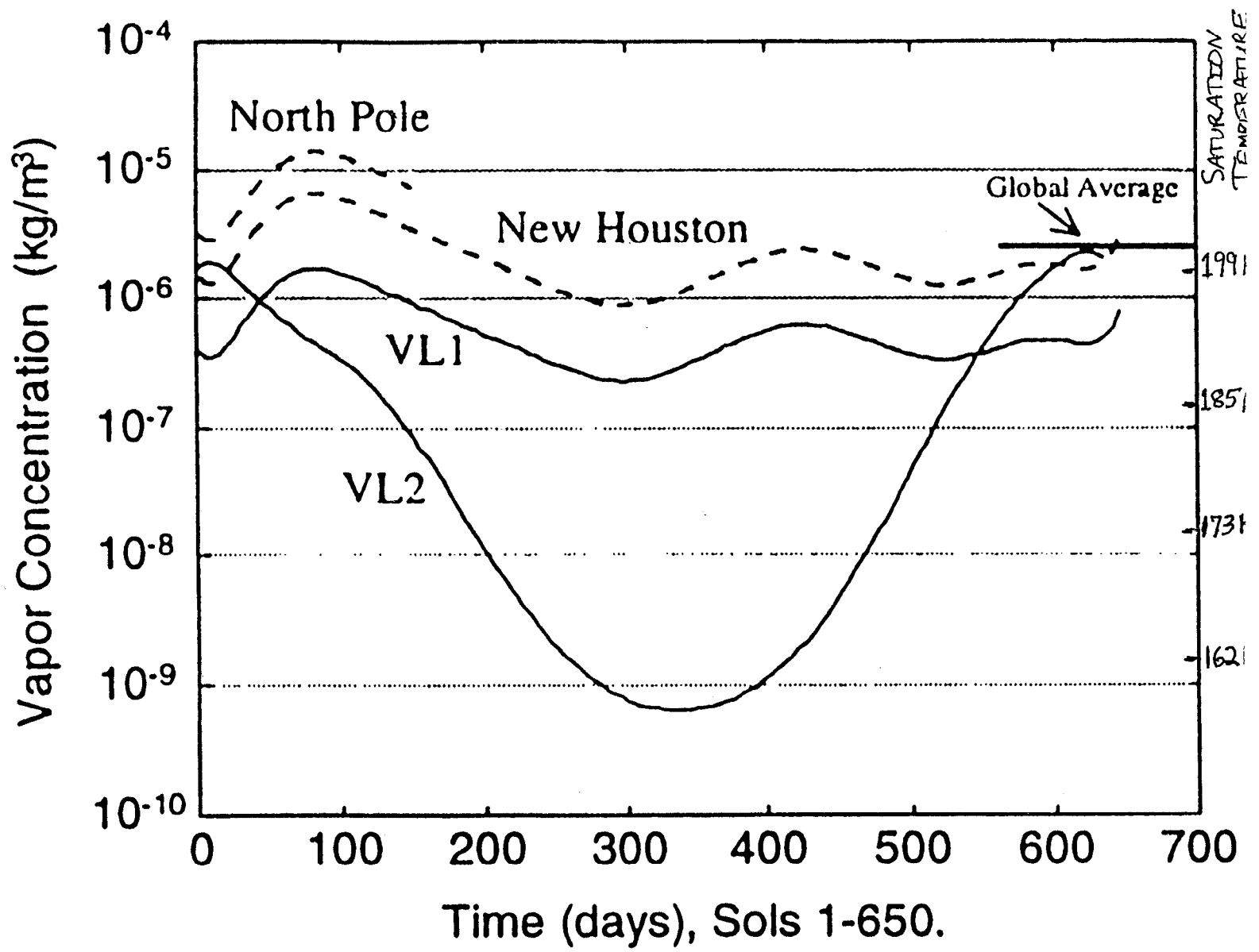
Eventually, sustained-and-concatenated exercising of human ingenuity will reduce the cost of a first human expedition to Mars to levels such that even non-governmental resources will suffice to sponsor it. We offer the Martian water-plant sketched in the foregoing as a stone for use in raising this great edifice of technology-and-intellect.

## **Figure Captions**

**Figure 1.** Water content of the Martian surface-level atmosphere versus time in Martian days (Sols) observed indirectly by the Viking Lander 1 (VL1) and Viking Lander 2 (VL2). The VL1 data-set is significant more consistent with other measurements of Martian atmospheric water content, and thus is used as the basis for the calculated seasonal variation of the globally-averaged atmospheric water content, which is labeled 'New Houston.' The globally- and seasonally-averaged value is labeled 'Global Average.' [After Grover and Bruckner, AIAA Paper 98-3302] The vertical right axis indicates the temperature at which the water vapor content on the left vertical axis is the saturation vapor pressure, i.e., below which temperature water will condense from the air.

**Figure 2.** The mass budget of a manned expedition to Mars consisting of a crew-of-four, which stays on Mars the 400-day fraction of the synodic period corresponding to minimum-energy trajectories from Earth-to-Mars and then from Mars-to-Earth. [After Hyde, Ishikawa & Wood, UCLLNL PHYS-BRIEF 90-402] Note that the fraction of the total expedition's mass budget leaving a Deimos parking-orbit which is water(-equivalents) is  $\geq 80\%$ .

**Figure 3.** An artist's conception of the two primary types of Mars surface-exploration vehicles. A RL-10-based rocket propulsion unit – dubbed a 'Hop-About' – is used for ballistically transporting a pair of expedition crew-members and a surface rover (descended from the Apollo Lunar Rover) from the expedition's Base to many other sites on the planet. At any such secondary exploration site, the  $H_2/O_2$  fuel-cell-powered rover is roll-on/roll-off-deployed from its stowage-point on the Hop-About to carry the crew-pair and their equipment around for local exploration. All of the consumables of the exploration transportation system – propulsive mass, cryogenic fuel cell feedstreams and life-support fluids – thus are water-derived. [After Hyde, Ishikawa & Wood, UCLLNL PHYS-BRIEF 90-402]



**Figure 1.**

# MARS/DEIMOS EXPEDITION MASS BUDGET

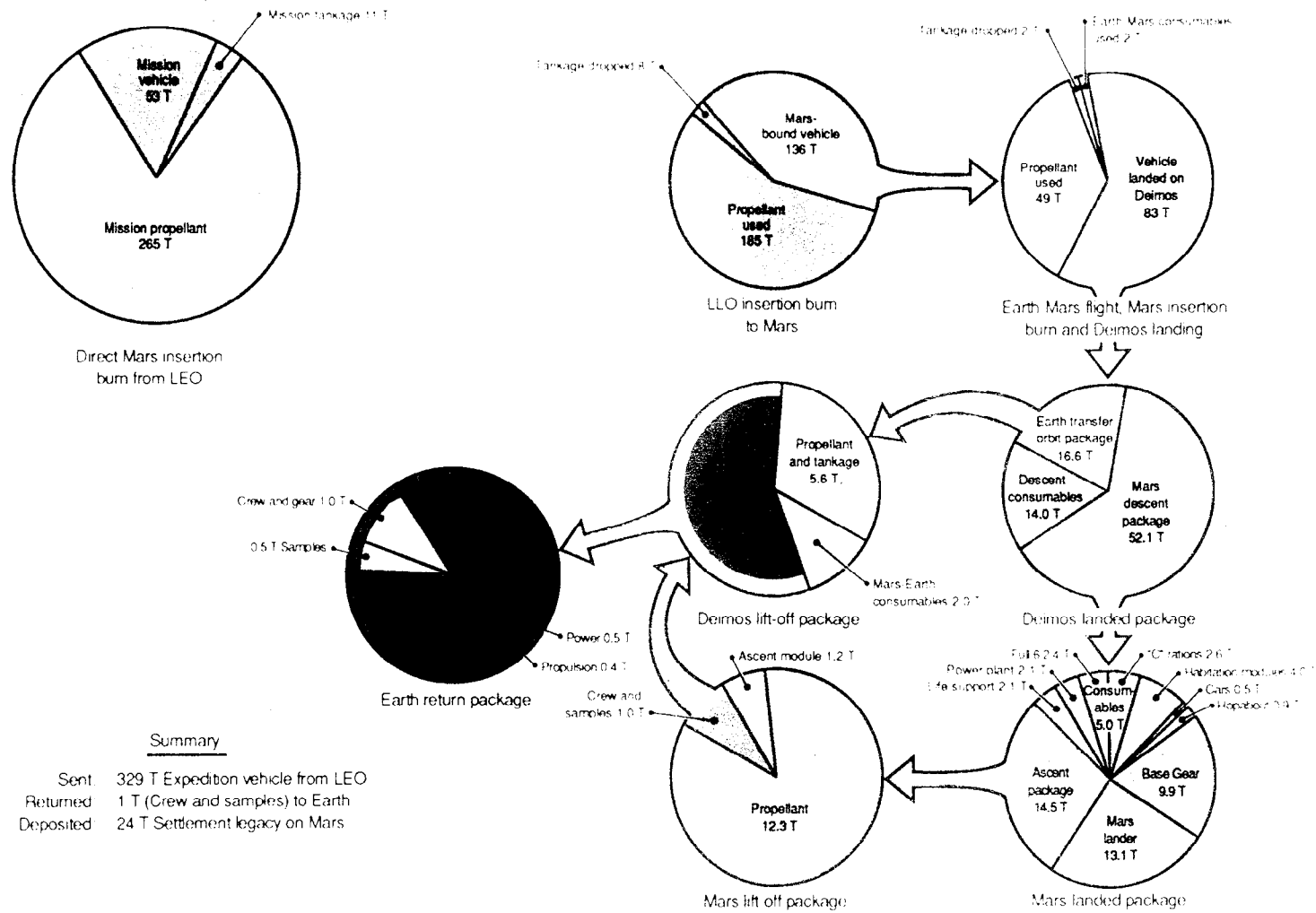


Figure 2.

Figure 3.

